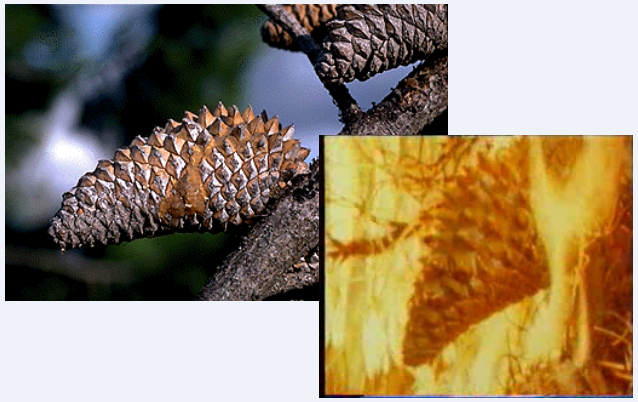
Fire and explosion in nature – some biomimetic possibilities



Andy McIntosh

Energy and Resources Research Institute, University of Leeds, England

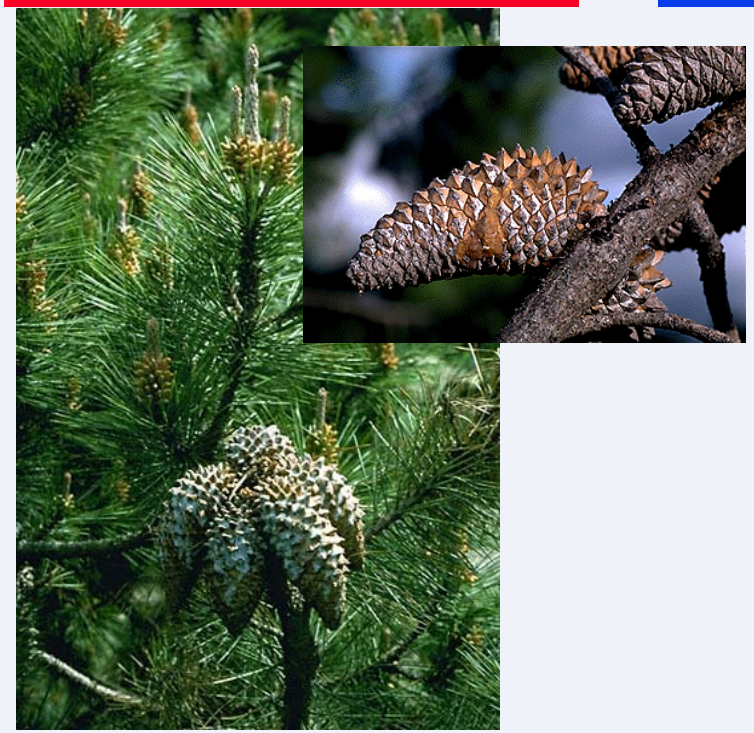
Three examples

- The knobcone pine - has a high temperature controlled unique gas emission insulating system.
- The scotch broom seed - has a mechanical, humidity controlled propulsion device for dispersing its seed.
- Biomimetic applications – knobcone pine : fireproofing; insulation by gas emission – relevance to intumescence behaviour of fire-proofed polymer seating used widely in air, road and rail transport.
- Biomimetic applications - scotch broom: propulsion; heterogeneous dispersal of nano powders in the pharmaceutical industry.

- The bombardier beetle - has a highly efficient mass ejection device involving a micro combustion chamber and a series of mini explosions.
- Biomimetic applications – bombardier beetle – pharmaceutical sprays, fuel injectors, gas turbine re-igniters, fire extinguishers, fire suppressant sprays.

• Knobcone Pine

Basic facts :

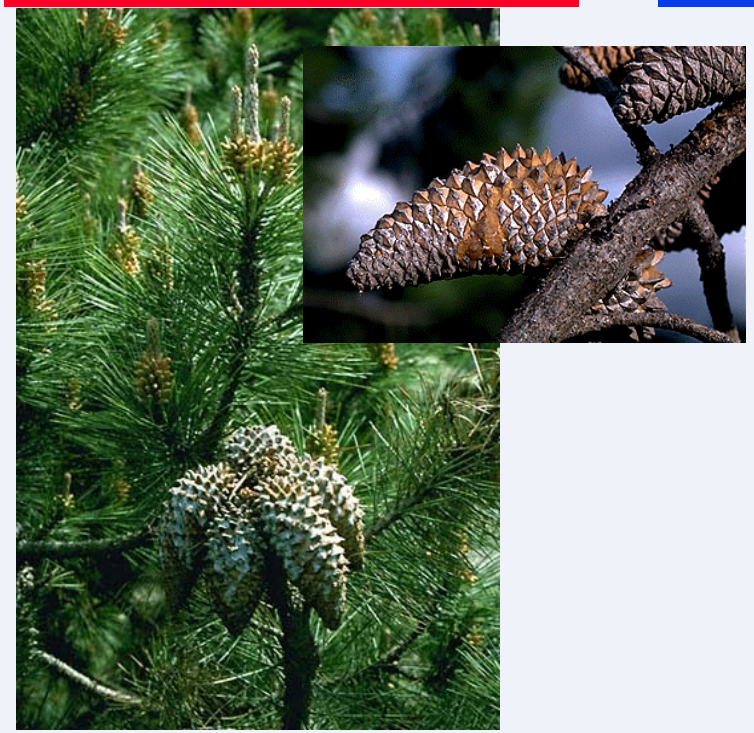


Knobcone Pine *Pinus attenuate* showing cones which can be as old as 30years before opening – only by the heat of a forest fire

- Grows on dry, rocky slopes and ridges of the coastal mountain ranges in NW USA; from southern Oregon to Baja, California.
- Elevation of between 800 -1350 m.
- Abundant cones between 8 and 15 cm. long, clustered in rings or ‘whorls’.
- Each cone is stalkless and turned back in an asymmetrical shape.

• Knobcone Pine

Basic facts :



Knobcone Pine *Pinus attenuate* showing cones which can be as old as 30years before opening – only by the heat of a forest fire

- Cones remain closed many years ~ even as much as 30 years.
- When forest fires kill the trees, cones open and shed their seeds. The abundant seedlings then begin a new forest.
- Each seed trapped in the cone is about 6mm long with a ‘wing’ attached, approximately 2.5 - 3 cm. long

Very hard cone

Nothing opens it for decades – except…

Fire!

…but only partially opens

Insulating gas emitted first

Gas emission protects seed

The dead tree

…but then cones fully open

The seed falls

…and the forest is reborn.

The intricate mechanism of the Knobcone Pine

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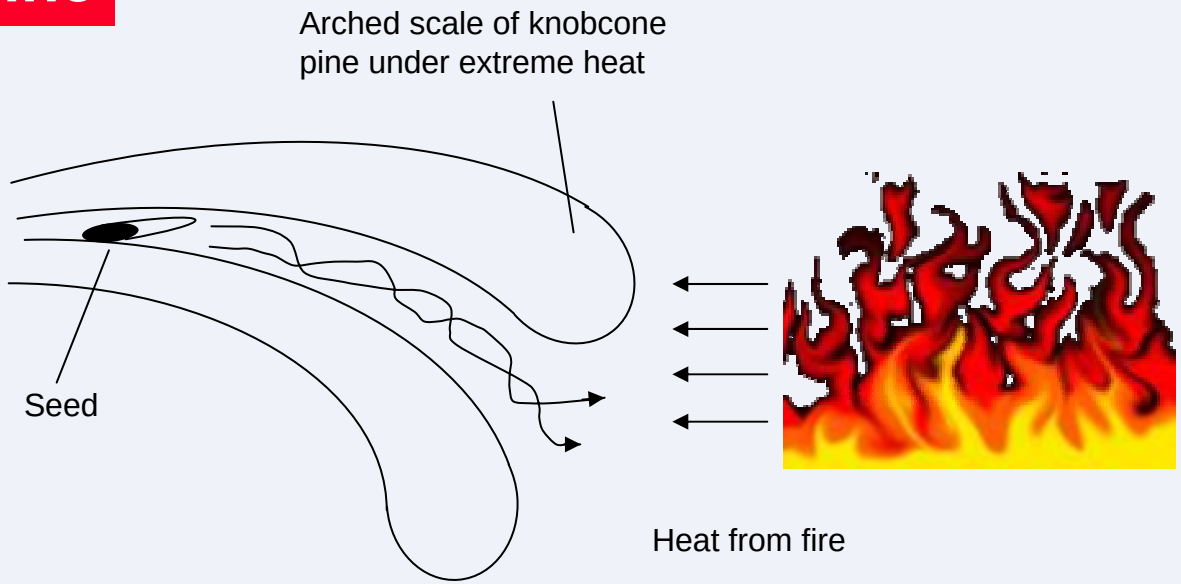
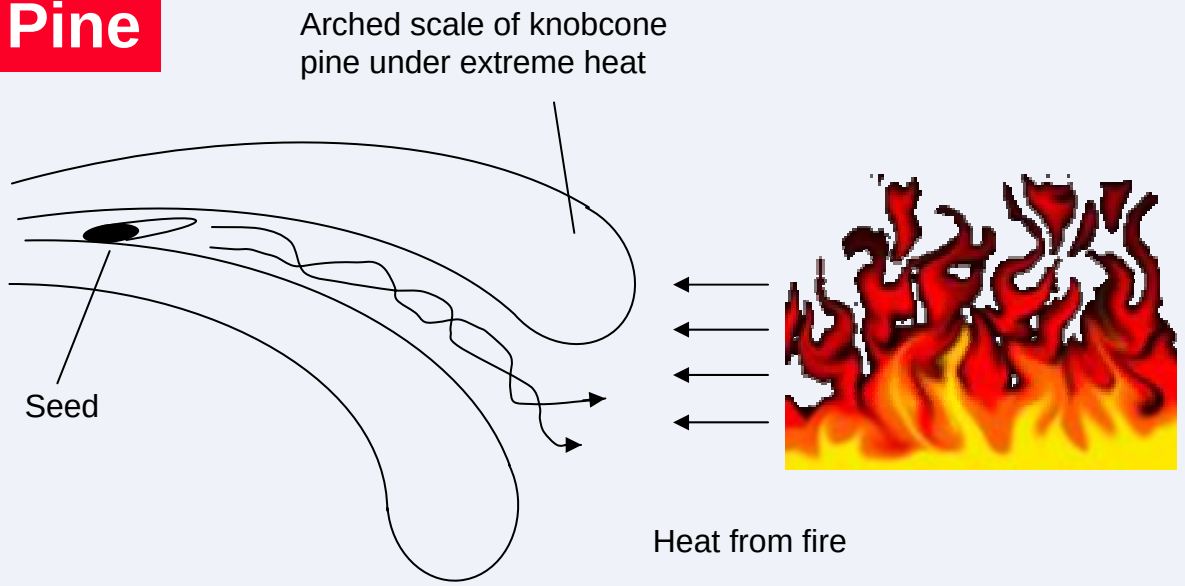
• Knobcone Pine



Partially opened scale of knobcone pine during fire

• Knobcone Pine



- Opening of cones very gradual after heating in the fire.
- Typical times for seed to start falling are 1 to 12 hours after fire - when ground has cooled.
- Arched scales continue to slowly expand and drop seed for at least 4 post-fire years.
- Scales partially contract during periods of rain or other high relative humidity, but resume expansion when relative humidity drops.

• Knobcone Pine

Possible biomimetic applications

- Cones themselves : Material properties of differential expansion of the layers in each scale produce the opening and closing mechanism. Each cone will differ as to its characteristic temperature so there is a clear biomimetic application in categorising the critical temperature and humidity for each type of cone.

- Resin used : The tough resin which seals the cone liquefies at 203°C. Coupled with the material of the scales there is the potential here for biomimetic applications to fireproofing.

• Scotch Broom

Basic facts :

Scottish broom plant showing the typical yellow flower found in most species in the wild.

- Broom found widely in the British Isles, Europe, North America and in the southern hemisphere in Tasmania and cooler regions of Australia.
- Colour of broom flower in the wild is generally yellow. Cultivated brooms can be variegated. Some can have scarlet red on the wings of the flower with yellow in the centre (Lena's broom) or a maroon red such as the Burkwood broom.
- Flowering most abundant on plants more than 4 years old.
- Can grow from 0.3 to 0.75 metres a year and attain heights of over 2.5 metres.
- Most plants have a single base with many upward spreading branches.

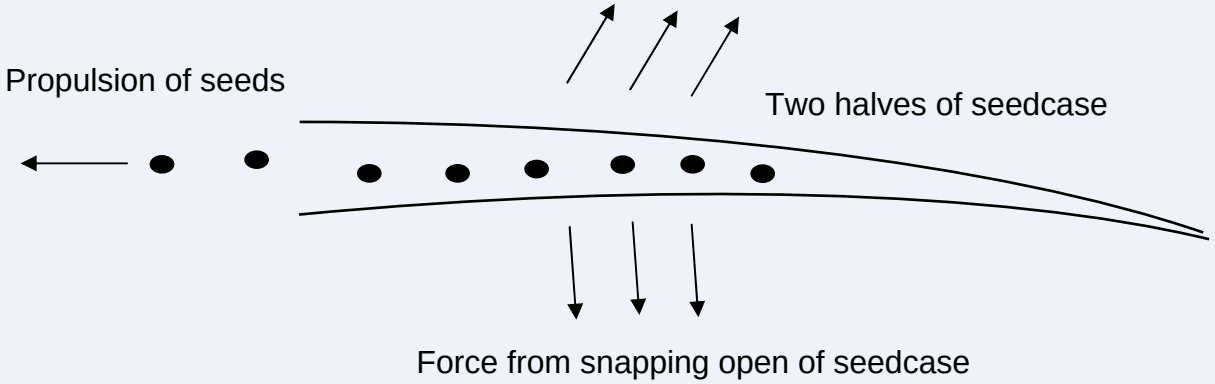
- **Scotch Broom**

Seed dispersal

Scottish Broom seedpod. When the pod dries out, the warping of the two halves is in opposite directions leading to an unstable critical point when the seedpod bursts, shooting the seeds as much as 4 metres from the original plant.

• Scotch Broom

Seed dispersal



- Seed is usually black, hard-shelled, and similar in shape to a pea.
- Encased in flattened seed pod covered with fine soft hairs ~ 5 cms. long.
- Seed pod dries at maturity.
- Two halves of the pod warp in different directions.
- Eventually snaps open - throws seeds from 1 to 4 metres away with a considerable explosive force

• Scotch Broom

Possible biomimetic applications

- The throw ratio (typical throw distance divided by seedpod length) is typically 40.

- Experiments

– need to measure the maximum tension typically holding the two halves of the seedpod before they separate.

– measure impulsive force exerted by the two halves of the seedpod on the seeds.

– measure energy stored in strained state.

• Scotch Broom

Possible biomimetic applications

- Considerable advantage for controlled powder dispersion in pharmaceutical applications :

a) powder needed without bulk of coiled spring delivery or the use of a small chemical explosive.

b) propulsive device which simply depends on two warped pieces of material under tension with a small barrel or funnel.

c) triggered open either mechanically or by drying.

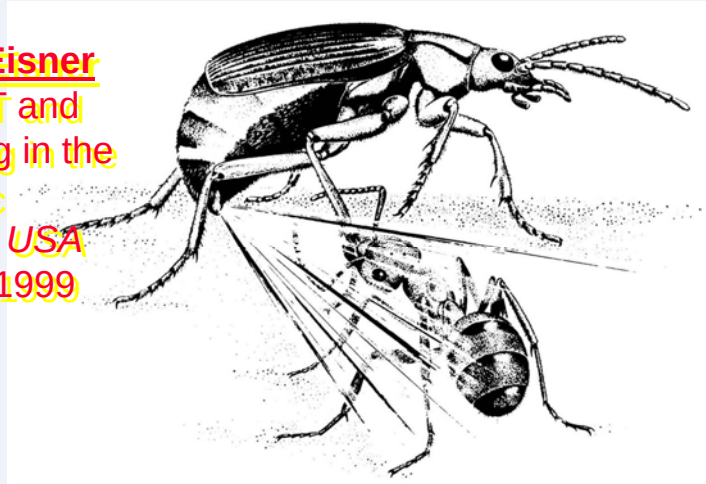
- Application to more precise means of delivery than conventional heterogeneous sprays.

Bombardier Beetle

• The Bombardier Beetle

Bombardier Beetle defence mechanism :

From work of Professor Tom Eisner of Cornell University : Eisner, T and Aneshansley, D. J, "Spray aiming in the bombardier beetle: Photographic evidence", *Proc. Natl. Acad. Sci. USA* Vol. 96, pp. 9705–9709, August 1999



• The Bombardier Beetle

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'Windy' beetle found at reserve

A beetle which breaks wind as a defence mechanism has been found living near a power station in south Wales.

The bombardier beetle has a unique way of defending itself

The bombardier beetle fires a noxious, smelly chemical around 100 C in temperature from its bottom at any predator which tries to attack it.

And conservationists have found it living on a nature reserve near the Aberthaw Power Station in the Vale of Glamorgan.

The beetle - *Brachinus crepitans* - measures between six and 10 millimetres and makes the sound of breaking wind when defending itself when under attack.

It is the first time it has been spotted at the site since the 1980s.

Alex Coxhead, who is the reserve manager for the Wildlife Trust of South and West Wales, looks after the Aberthaw Lagoon and Saltmarsh nature reserve for the owners of the power station Innogy.

"The beetle is very clever because it has developed this

"It makes a sound like a 'parp' with a lot of smoke and

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- **The Bombardier Beetle**

Experimental work of Eisner

From the film ‘Alien Empire’, BBC

- **The Bombardier Beetle**

Experimental work of Eisner

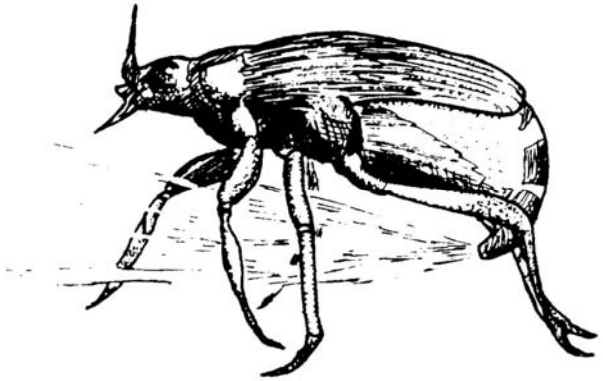
Professor Tom Eisner, Cornell University

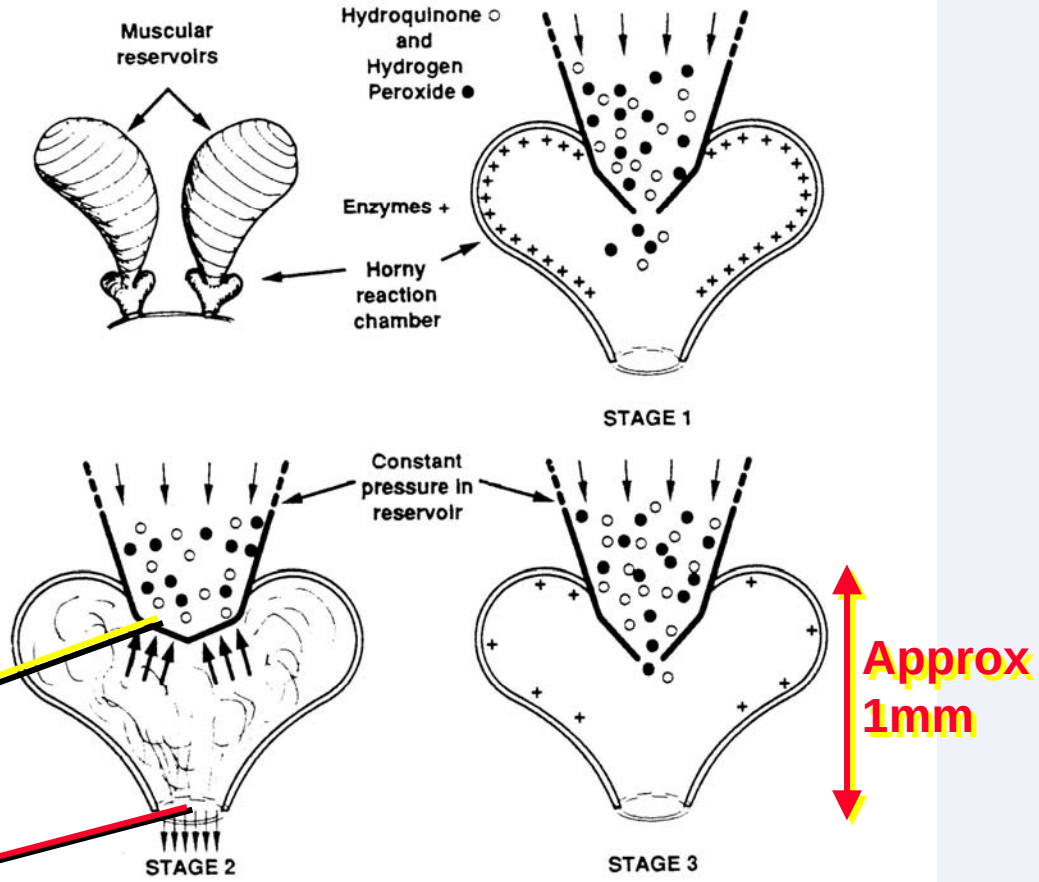
From the film ‘Secret Weapons’, BBC

• The Bombardier Beetle

Experimental work of Eisner

Bombardier Beetle – Pulse combustion par excellence.





Fuel-inlet valve opened at low pressure, closed at high pressure.

Exhaust-outlet at high pressure……

…..but latest finding is of a sophisticated pressure release valve at outlet

- **The Bombardier Beetle**

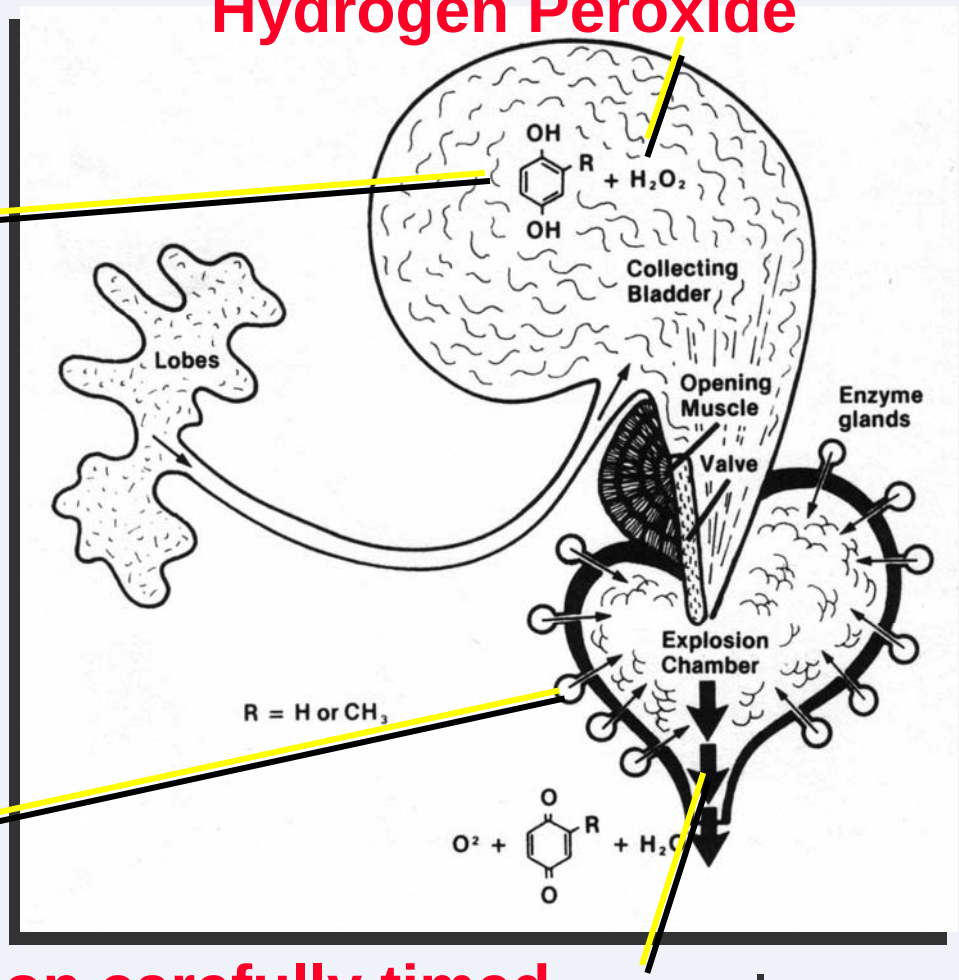
Experimental work of Eisner & Schildneckt

Explosion Chamber of Bombardier Beetle

Hydrogen Peroxide

Hydroquinone

$$C_6H_6O_2 + H_2O_2 \rightarrow C_6H_4O_2 + 2H_2O$$



Enzymes – Catalase and Peroxidase

Catalytic combustion carefully timed

Chemical Reactions within Bombardier Beetle

Aqueous solution of reactants is stored in a reservoir, and is composed of hydroquinone $C_6H_6O_2$ at a concentration of 25% and hydrogen peroxide at concentration of 10% - Holoubek and Schildknecht

Salient steps

$$C_6H_6O_2(aq) \longrightarrow C_6H_4O_2(aq) + H_2(g) \qquad \Delta H_2 = +177{:}232\ Jmol^{-1}$$

$$H_2O_2(aq) \longrightarrow H_2O(l) + \tfrac{1}{2}O_2(g) \qquad \Delta H_3 = -94{:}5\ Jmol^{-1}$$

$$H_2(g) + \tfrac{1}{2}O_2(g) \longrightarrow H_2O(l) \qquad \Delta H_4 = -285{:}5\ J\ mol^{-1}$$

Overall Reaction

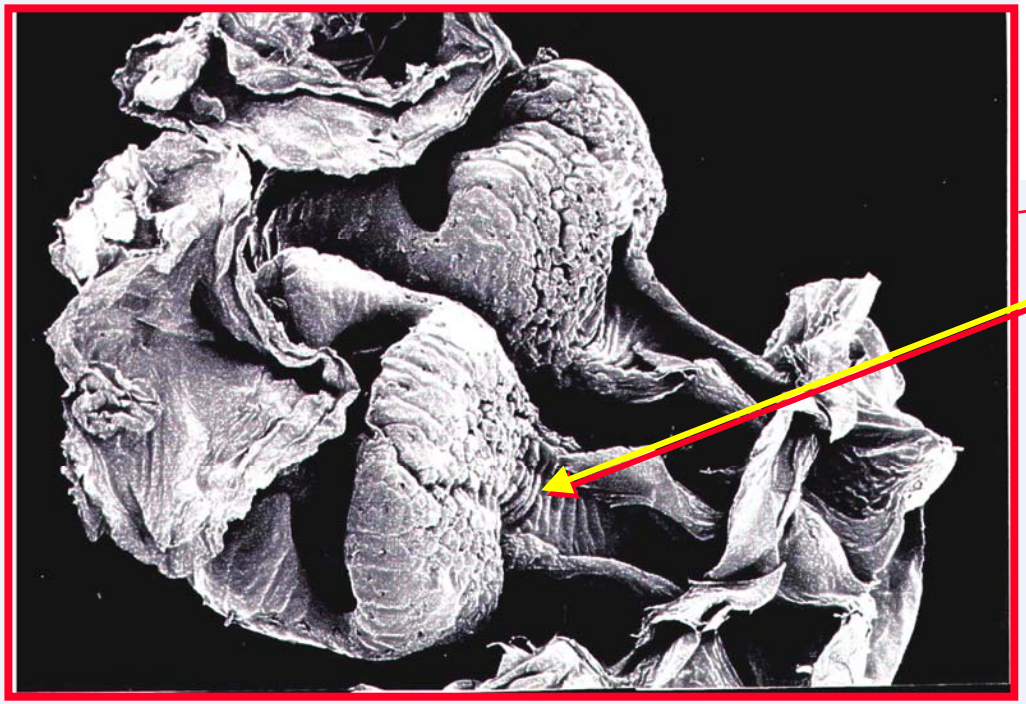
$$C_6H_6O_2(aq) + H_2O_2(aq) \longrightarrow C_6H_4O_2(aq) + 2H_2O(l) \qquad \Delta H_1 = -202.8\ Jmol^{-1}$$

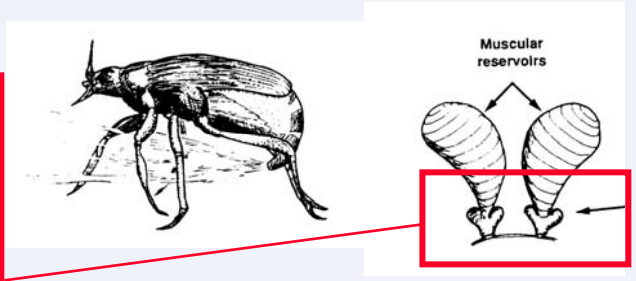
Total heat release for one kilogram of solution is then 794.2 kJ/kg solution

• The Bombardier Beetle

Experimental work of Eisner

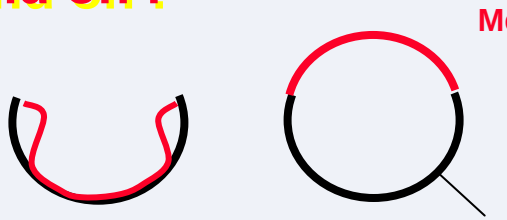
Exit valve observations





The pressure release valve that controls the expulsion of the hot jet.

End on :



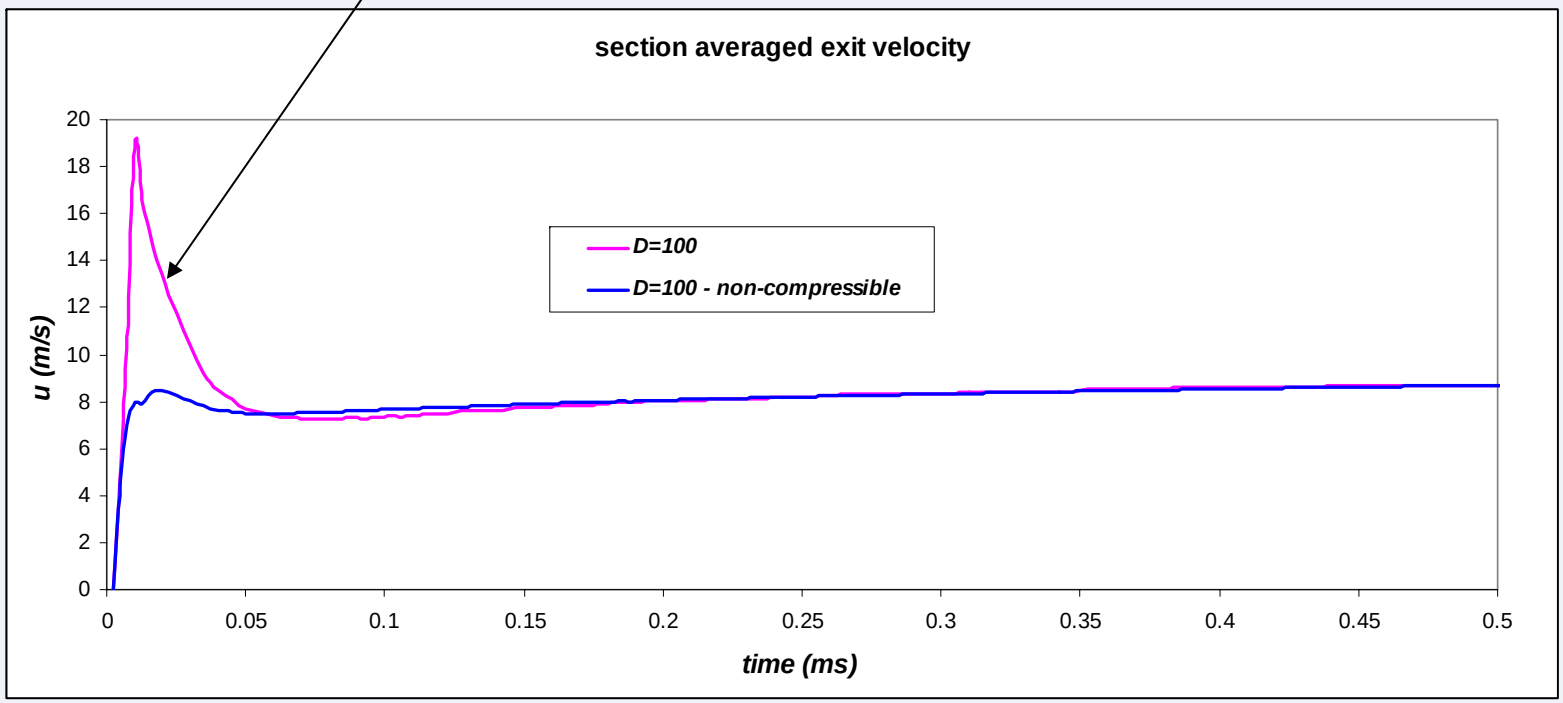
The twin combustion chambers and nozzles in the *Carabidae Crepidogastrini* Beetle from a dissection by Eisner (2002)

- Major influence of the pressure release valve – this creates a 'trigger pressure' so that hot water now undergoes 'cavitation' explosion by pressure drop

• The Bombardier Beetle

Modelling using steam explosion

Effect of compressibility of steam

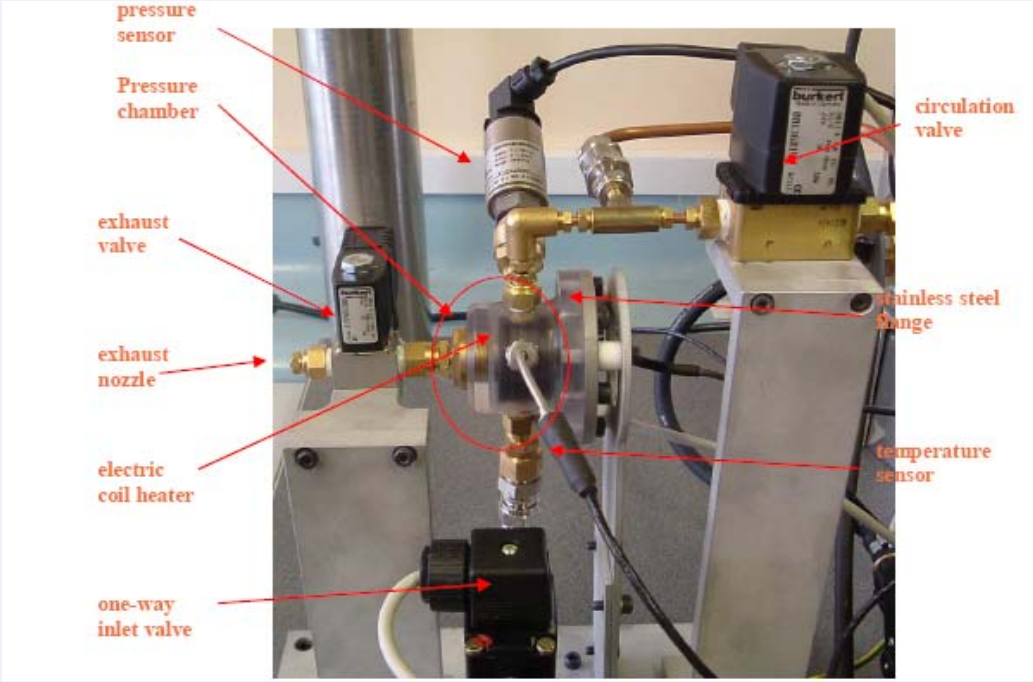


Measurements in 10^{-3} mm

- The Bombardier Beetle

μmist™ experimental rig

Experimental rig built and tested to mimic the physics of the Bombardier Beetle chamber – approx 20 times the 1mm combustion chamber of the Beetle.



• The Bombardier Beetle

μmist™ experimental rig

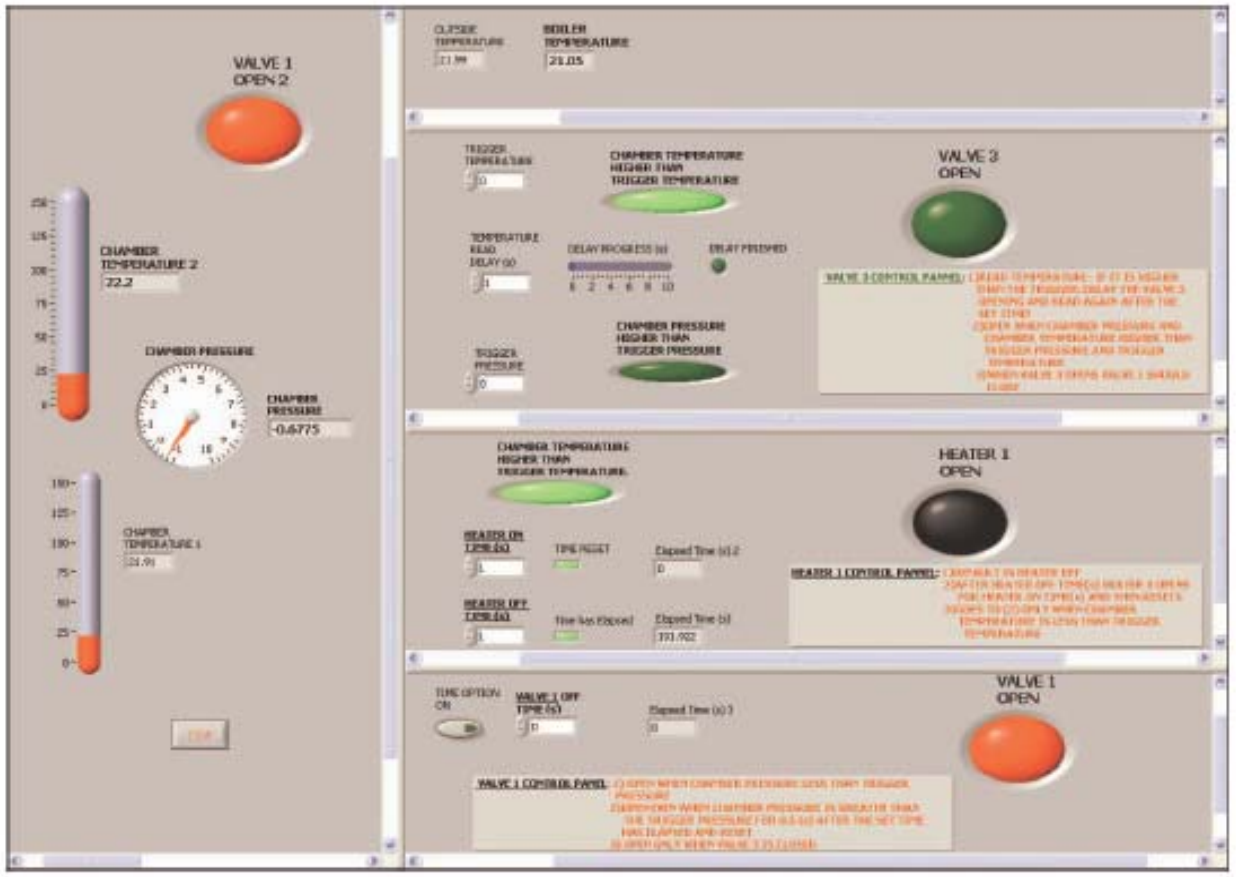
- Heating done by electrical coil.
- Chemistry not mimicked.
- Cavitation explosion with crucial timing of valves

The rig in action with large droplets and near maximum mass ejection .

• The Bombardier Beetle

μmist™ experimental rig

Digitally controlled valve system



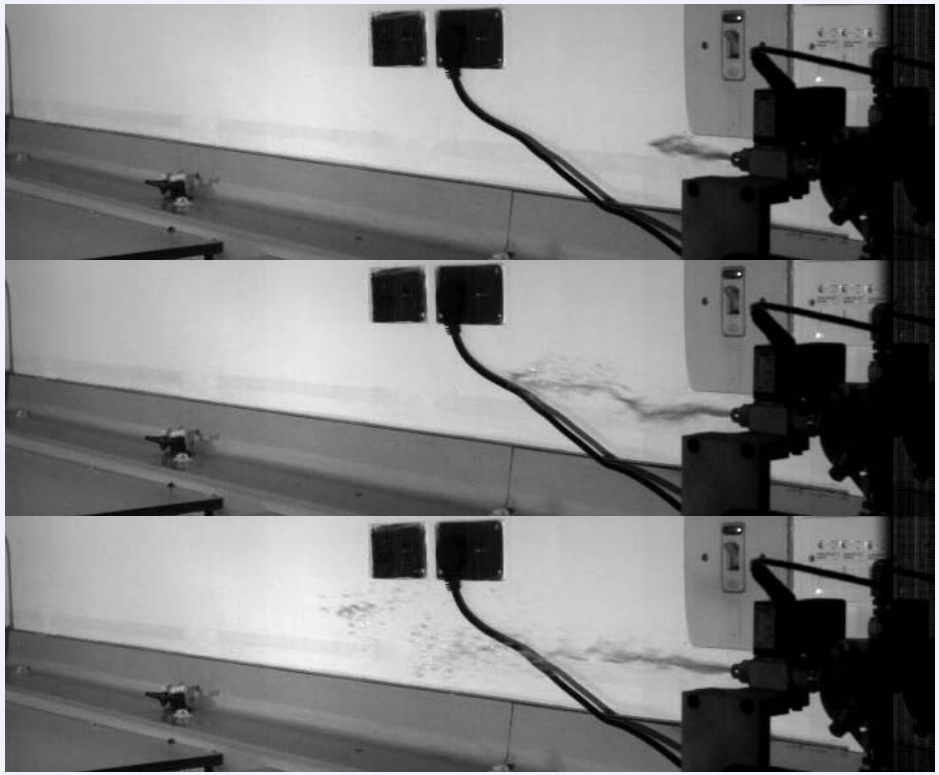
Fire and Explosion in Nature

University of Leeds : Biomimetics Network

- The Bombardier Beetle

μmist™ experimental rig

Single exhaust showing large throw ratio – near maximum of 4m



- The Bombardier Beetle

μmist™ experimental rig

Exit velocity measurements

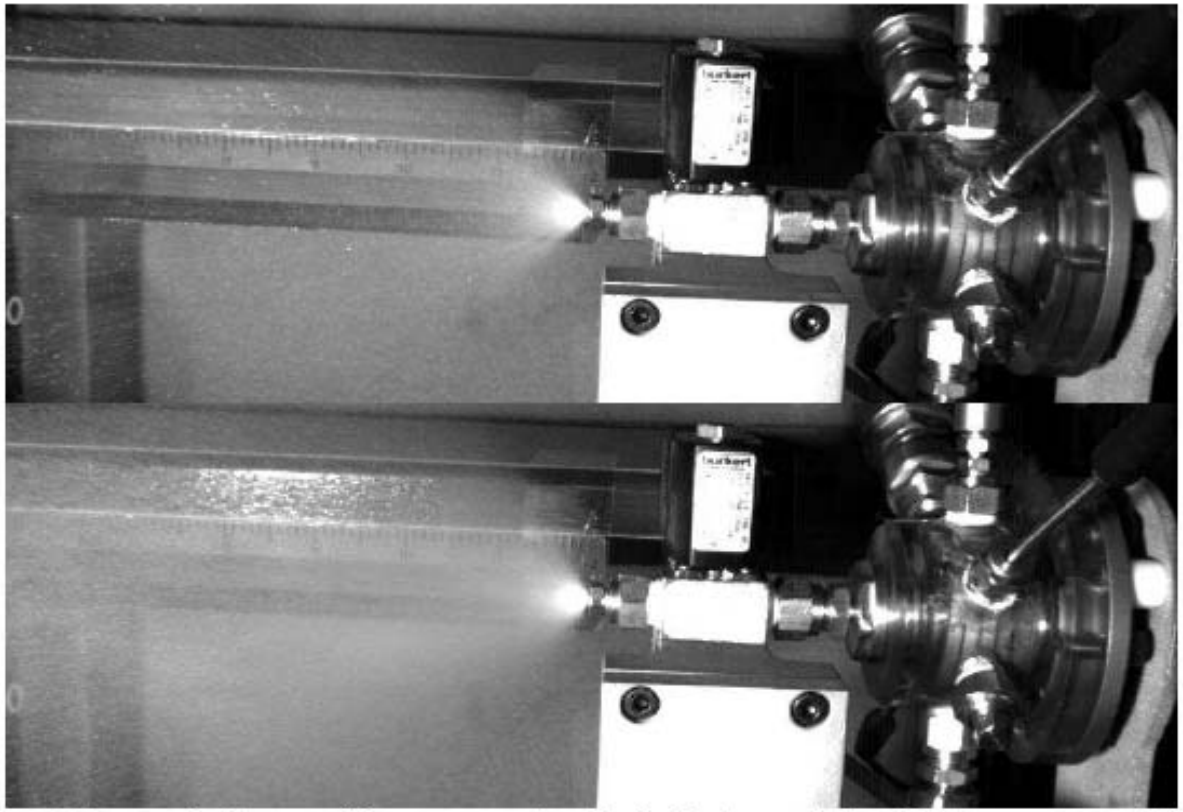


Fig. 9. Two single frames of the ejection taken by the high speed digital video camera at 1500 frames per second. The first frame (top) is taken at 93ms and the second one (bottom) at 123ms after opening the exhaust valve. In this experiment it was intended to measure the exit velocities from the nozzle. For this purpose a ruler is installed behind the nozzle in line with its axis to allow keeping track of some individual droplets positions in time for velocity measurements.

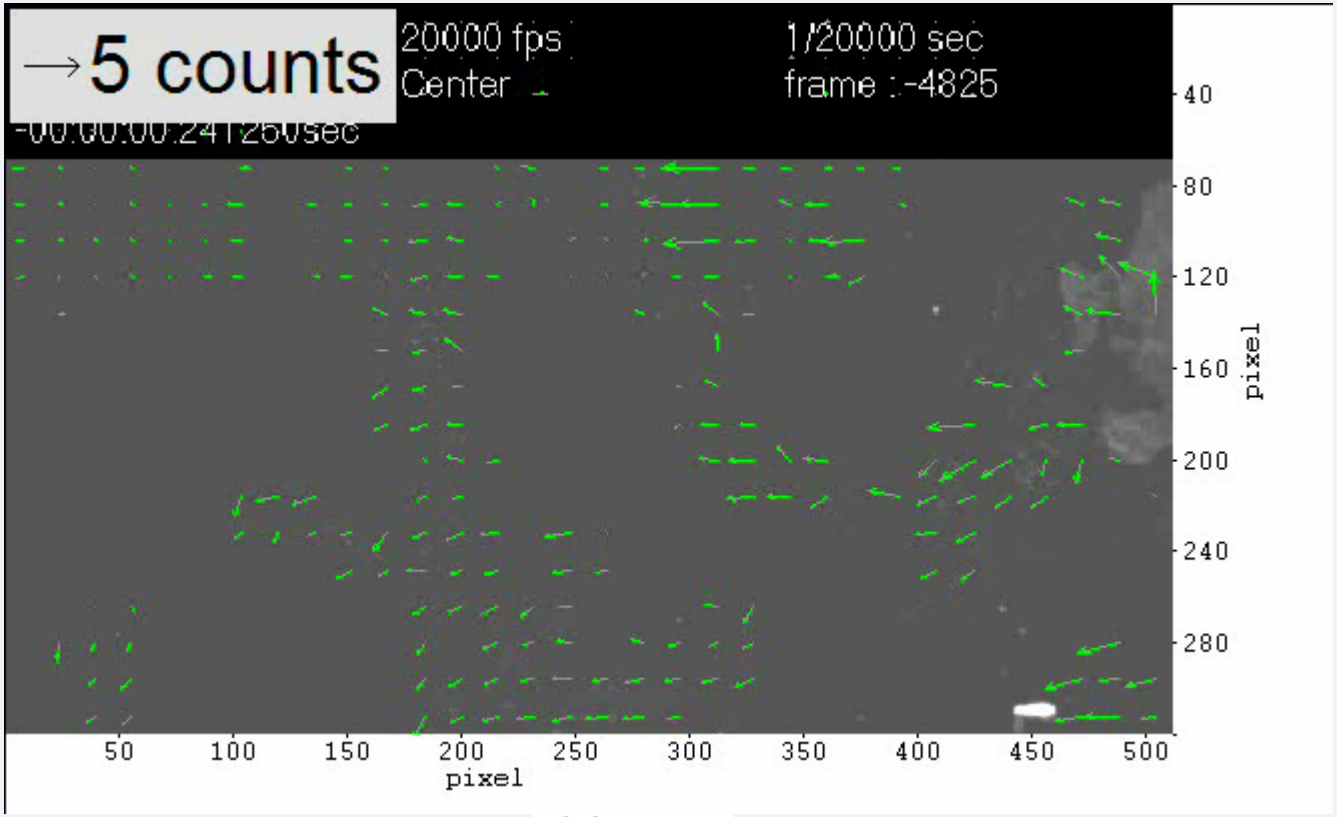
- The Bombardier Beetle

μmist™ experimental rig

PIV Processed sample

Temperature = 132 V3 closed time = 120ms (frequency = 8Hz)

Nozzle Diam. = 0.5mm



20 mm

Max velocity approx 10 m s^{-1}

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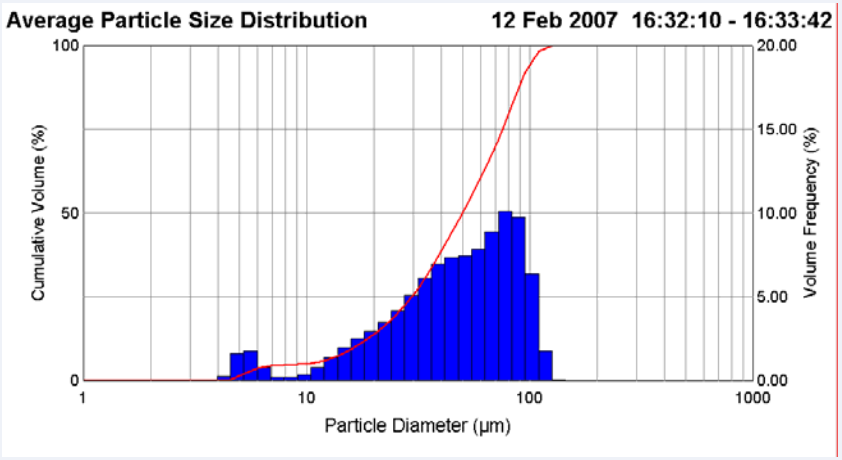
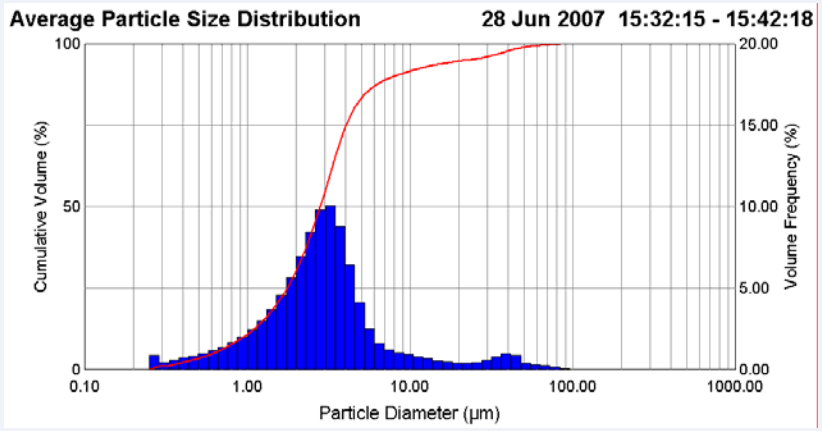
Example – 0.5mm nozzle :





Large droplet size

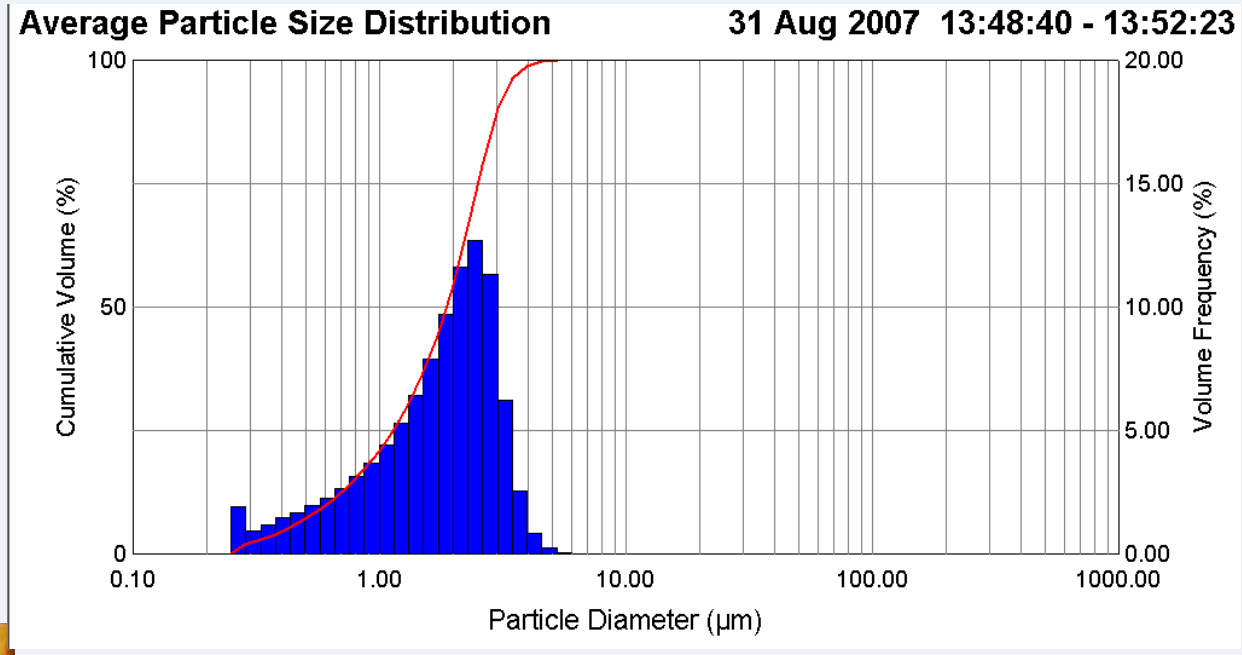
Small droplet size

A typical distribution of droplet sizes for 0.5mm diameter nozzle. The distribution will depend on factors related to nozzle diameter and operating conditions (trigger pressure and chamber volume, time setting of opening and closure of valves)..

- The Bombardier Beetle

μmist™ experimental rig

Example of very fine droplets - sub 5μm case with 2mm nozzle and restricted inlet flow



Fire and Explosion in Nature

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Medical Applications

- Water Vapour or Organic Carrier Medium
- Nebulisers
- Drug Delivery Systems

Fuel Injection

- Small droplet size
- Increases fuel burning efficiency
- Improving fuel consumption
- Minimising exhaust pollution

Fire Extinguishing

- Fire Suppression
- Optimal mist adjustment in real time
- Water vapour alternative to Halon

CONCLUSIONS

- Two examples in nature are considered where fire and explosion are involved in seed dispersal. The use of such extremes shows the intricacy of design features which biomimetic engineers have come to expect in the rich and diverse mechanisms in biological systems in nature.
- The exploratory studies show that there are potential advantages in studying the material properties of the knobcone pine and its resin, the tensional behaviour of the seedpod of the scottish broom, and the mass ejection device of the bombardier beetle.
- Studies in the Bombardier Beetle have led to development of the μmist™ technology with applications to pharmaceutical sprays, fuel injectors, fire extinguishers and further ahead possible aeroponic and jet engine igniter applications

References : McIntosh, A.C. "Combustion, fire and explosion in nature – some biomimetic possibilities", *Journal of Mechanical Engineering Science*, Series C, Vol 221 Special issue on biomimetics, pp. 1157-1163, 2007

Beheshti, N, and McIntosh, A.C., "The bombardier beetle and its use of a pressure relief valve system to deliver a periodic pulsed spray", Bioinspiration and Biomimetics, Vol 2, pp.57-64, 2007

For the Bombardier Beetle work, thanks are due to EPSRC and Swedish Biomimetics 3000® for their sponsorship. SB 3000® own the license to this technology and have very generously funded the project to pre-prototype stage.